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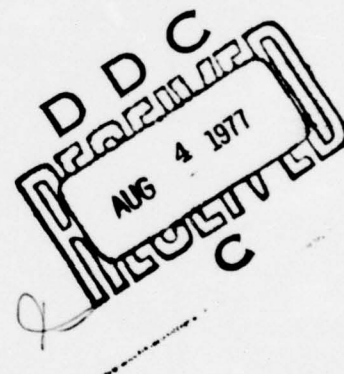
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MATERIAL SELECTION CONSIDERATIONS FOR FLUORIDE THERMAL ENERGY STORAGE CONTAINMENT IN A SODIUM HEAT PIPE ENVIRONMENT

ARIZONA STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
TEMPE, ARIZONA

MAY 1977

TECHNICAL REPORT AFAPL-TR-77-9
FINAL REPORT FOR PERIOD JUNE 1976 - AUGUST 1976



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E.T. Mahoney
Name

Name
Project Engineer

Jerry E Blaw
Name
Project Engineer

Name _____
Project Engineer

FOR THE COMMANDER

Joseph W. Wil

Name and Title

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FOREWORD

This final report was prepared by Professor Dean L. Jacobson, Arizona State University, under the Air Force Aero-Propulsion Laboratory's Senior Investigator Program, Project 2014, Task 7, Contract F33615-74-C-2014. Jerry E. Beam and Tom Mahefkey, AFAPL/POE-2, are the cognizant Air Force Project Engineers.

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SUMMARY

This report is the result of a literature survey of material for high temperature application to space environment and to sodium containment near 1400°F for thermal energy storage, Vuilleumier cryocooler heating.

Candidate thermal energy storage capsule materials include stainless steels, superalloys, and refractory metals. Refractory metals are excellent candidates for the application except that they cannot be operated in air, a probable requirement prior to a space launch. The refractories are also costly, difficult to fabricate and result in a weight penalty in some cases.

Little information has been found in the literature on the behavior of superalloys either in the high temperature space (vacuum) or alkali metal (sodium) environments. Liquid metal fast breeder reactor (LMFBR) programs have generated considerable corrosion and mechanical property data for stainless steels in a Na environment up to 1000°F. Higher temperatures for some nuclear requirements are now leading designers to consider superalloys because of their superior high temperature strength as compared to stainless steels. It has been found that the corrosion capabilities of stainless steels diminish above 1000°F. These high temperature needs are encouraging new research on superalloys for high temperature alkali metal environments. In this paper, the strength and corrosion characteristics for both the space and sodium environments are reported for a number of candidate materials.

A number of program recommendations are made, based upon the findings of the survey. These include life-tests of candidate materials in a sodium environment with post test corrosion evaluations.

A literature survey of Na heat pipes resulted in recommendations that a few of the most promising materials be fabricated into heat pipes and life-tested with subsequent corrosion analyses. Experimental determination of wicking heights of Na is also found to be critical for accurate design of the heat pipes. Na handling and heat pipe loading procedures need to be established.

SECTION I

INTRODUCTION

A literature survey is reported, which was conducted to obtain information to aid in the material selection for thermal energy storage containment ampules which are exposed to a high temperature sodium atmosphere, the sodium being part of a heat pipe structure. The sodium heat pipe region is in turn encased in a second container which at the same high temperature is exposed to space. The material selection problems thus involve first, the thermal energy storage material (currently a fluoride salt); secondly the sodium environment; and thirdly, the space environment. This paper concentrates on the latter two aspects of material compatibilities. The strength and corrosion characteristics of a number of superalloys and stainless steels are evaluated for the space and sodium environments. In space, the evaporation rate of high vapor pressure alloying elements can lead to changes in composition of the material and therefore possible reductions in strength and lifetime. In the liquid sodium environment a number of corrosion mechanisms can occur which can either remove material, reducing strength directly or produce changes in composition. General requisites for long-life are that the sodium flow velocity must be low, the oxygen impurities must be low and coupling of dissimilar materials should be avoided.

This review of the literature has revealed in general that little information regarding the compatibility of sodium with structural materials exists except in the case of a number of stainless steels which have been examined extensively for the liquid metal fast breeder reactor (LMFBR). In this case 304, 310, 316 and 347 stainless steels have been examined by

a number of investigators in sodium environments of varying conditions. At test temperatures, about 1000°F, these materials have demonstrated varying degrees of acceptability for the nuclear application. At the temperature of interest for the thermal energy storage application, 1000°F to 1400°F, the stainless steels have not demonstrated acceptable performance in the corrosion environment, nor is their strength of acceptable standards for this application. It appears that a number of candidate superalloys should be investigated because of their high temperature strength advantage.

A few refractory metals have been investigated with regard to sodium compatibility. The manufacturing difficulties, weight disadvantage, and vacuum operation requirements of refractories make them less desirable than superalloys for this application.

SECTION II

MATERIAL COMPATIBILITY

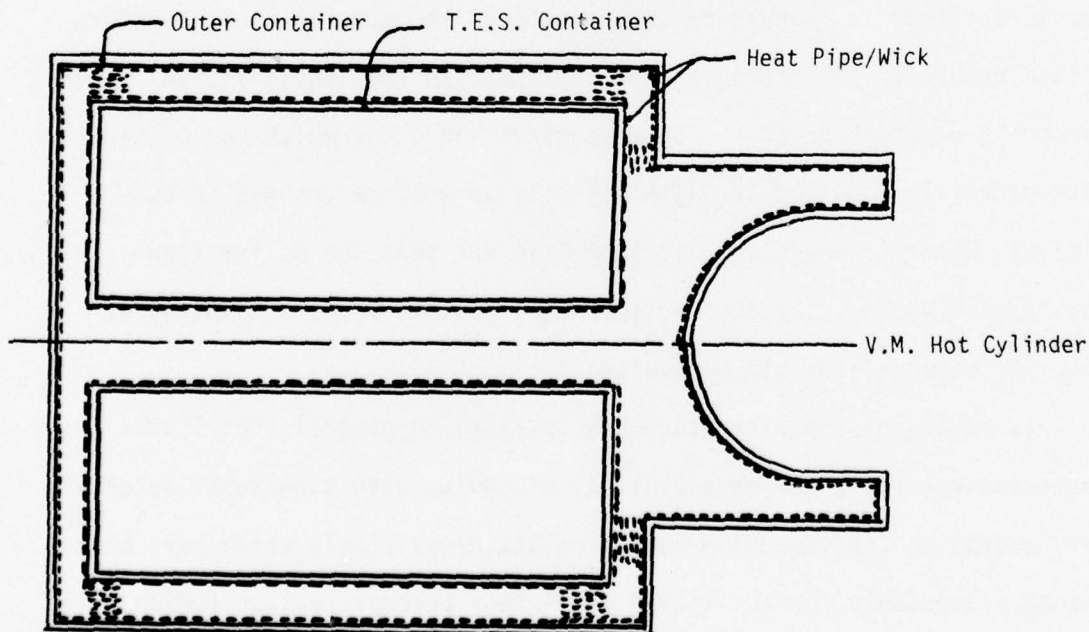


Fig. 1 Schematic of Compatibility Requirements for Integral Heat Pipe-Thermal Energy Storage System

Figure 1 is a schematic which shows the thermal energy storage material and containment capsule. The capsule's exterior is in contact with the sodium heat pipe. The heat pipe outer container is at approximately 1400°F and is exposed to the high vacuum environment of space. Selective evaporation of high vapor pressure components can lead to compositional changes and subsequent weakening of the structural member.

The liquid sodium environment which is in contact with both the thermal energy storage capsule and the outer heat pipe container can lead to a number of corrosion related problems.

The thermal energy storage capsule, on the inside, must contain the storage material (in this case, possibly a fluoride salt) with little corrosion.

2.1 Vaporization Considerations

Table 1 shows the vaporization rates of some pure metals at 1500°F. This is shown in terms of vaporization rate as centimeters per year, or mils per year to demonstrate the difference between materials with relatively low vaporization rates, like nickel, and those with high vaporization rates, like manganese. The vaporization rates of the refractory metals are many orders of magnitude less than those for the materials shown. The transition elements, nickel cobalt, iron, and chromium are intermediate between the refractories and other metals, such as manganese as shown, and other high vapor pressure alloying elements, such as sulfur, phosphorus, zinc, magnesium, copper, and aluminum. Recent data for superalloy Incoloy 800 demonstrates the vaporization characteristics of the constituent alloying elements.

Table 1. Vaporization Rates of Some Pure Metals at 1100°K (1500°F)
(Ref. 1)

METAL	VAPORIZATION RATE	
	cm/year	mils/year
Nickel	9.9×10^{-7}	3.9×10^{-4}
Cobalt	1.8×10^{-5}	7×10^{-3}
Iron	4.1×10^{-5}	1.6×10^{-2}
Chromium	3×10^{-4}	1.2×10^{-1}
Manganese	50	19,700

Table 2 shows the mass spectrometer determination of vapor composition for the Incoloy 800. Incoloy 800 initially contained .05% C, 0.75% Mn, 0.5% Si; 21% Cr, 32.5% Ni, 0.38% Ti, 0.38% Al and 46% Fe. As shown in Table 2, upon first heating at 1300°K the percent of total pressure for Mn is initially 45% and for Cr is 46%. The Mn, although in very small percentage is vaporizing very rapidly at the beginning of heating. (Ref. 1)

Continued heating depletes the material in Mn as shown by the rapid decrease in vapor composition of Mn. Cr remains about the same while the Fe vapor composition increases to a plateau. The Ni is not evident in the vapor until extended heating at 1600°K for 35 hours. This indicates that the Ni is strongly bonded in this particular alloy lattice.

Activity data, and therefore vapor pressure data, from which Figure 2 was derived, was obtained for the steady-state which was achieved after heating at 1600°K for 35 hours. Prior to that heat treatment, compositional changes made these determinations improbable.

Table 2. Mass Spectrometer Determination of Vapor Composition of Incoloy 800. (Ref. 1)

Vapor Composition: % of total pressure				
<u>Initial</u>				
<u>T:K</u>	<u>Cr</u>	<u>Mn</u>	<u>Fe</u>	<u>Ni</u>
1300	46	45	9	-
1500	56	15	28	-
<u>Heated at ~ 1525K for 114m</u>				
1300	48	31	21	-
1500	45	9	45	+ trace Ni and Cu
<u>Heated > 1600K for 35 h</u>				
1300	54	18	25	3
1500	50	7	36	7

Figure 2 shows the evaporation rate of the alloy constituents from Incoloy 800 after heating for 35 hours at over 1600°K. The evaporation rate in cm/yr is plotted as a function of temperature. The primary alloying elements, Ni, Cr, Fe, and Mn are demonstrated. Data for the pure elements derived from the literature and experimental data

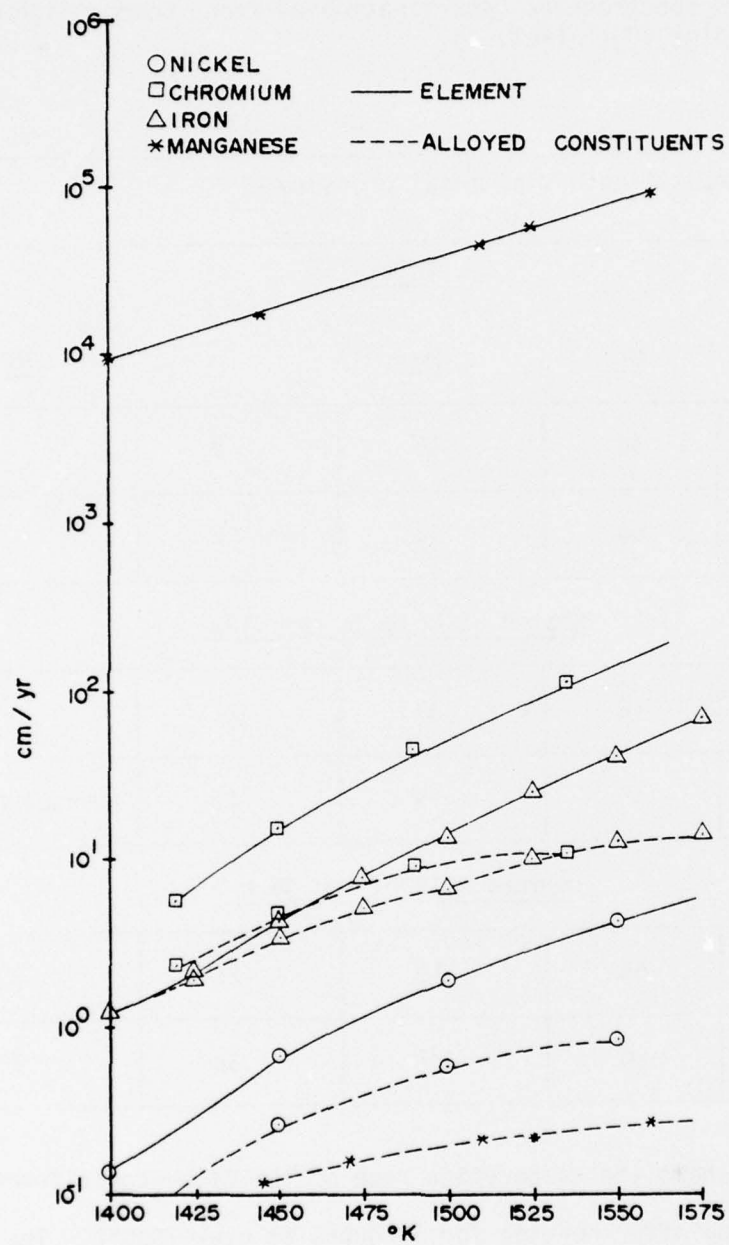


Figure 2. Evaporation of Alloy Constituents from Inconel 800 After Heating for 35 hours $> 1600^{\circ}\text{K}$ (Ref. 1)

for the alloy constituents are shown in Figure 2. It can be seen that in every case the evaporation of the alloyed elements is lower than the corresponding evaporation of the pure elements at a given temperature. These ratios would be expected to be in some accord with the composition of the alloy sample. The most drastic change, of course, can be seen in the vapor composition of the Mn which has dropped below that of the corresponding pure element. After steady-state conditions have been achieved, the Cr and Fe have the highest evaporation rates, the Mn being depleted during prior heating.

For a given application it must be determined what the reduction in Mn content or the content of any other alloying element will have on the structural characteristics or corrosion resistance of the alloy. The results in Figure 2 indicate that at high temperature the surface probably tends to be richer in Ni and poorer in Mn than the bulk material. The surface will become richer in Fe compared to Cr with time. The total pressure decreases as evaporation proceeds. The amount of Ni being lost is lower than would be expected relative to pure element vapor pressure data. The nickel appears to be bound tightly in the lattice, possibly partly with aluminum and one of the other lighter elements.

It should be noted in the Incoloy 800 work that vapor species between mass numbers 24 and 80 were measured. In this range Cr, Mn, Fe, Ni and Cr were found to be present in the vapor. The composition of the C, Si, Ti, and Al with mass numbers less than 24 were not measured. The Cu indicated in Table 2 appeared apparently an impurity.

2.2 High Temperature Properties of Candidate Materials

Table 3 presents the composition of a number of candidate containment alloys along with that of some other materials for comparative purposes. Table 4 shows that the strength and creep resistance, at 1500°F, of the stainless steels is consistently lower than that of the superalloys. The high strength characteristic of the superalloys is one of the primary reasons for their evaluation as containment materials. There are a number of alloys, such as Rene 41, which have exceptional high temperature strength, but are very difficult to fabricate and are therefore considered as candidates only where the additional strength is required. The Inconel and Hastelloy series are reasonable for cost-effective fabrication processes. In general the overall strength characteristics of the alloys must be matched to the expected loads in the system and designed to minimize weight and cost. Creep strength is very important for long term applications and at the desired temperatures little creep data is available for most of the materials.

2.3 Alkali Metal Corrosion (Sodium)

The alkali metal environment must be evaluated for a number of different destructive phenomenon. Corrosion is destructive attack by chemical or electrochemical reaction. Physical deterioration is by erosion. Often these phenomenon occur together, hence the term corrosion-erosion. Corrosion usually occurs by electrochemical mechanisms with four main types that might be observed in a Na heat pipe. A weight loss of the containment material by interaction with the Na can occur

Table 3
Some Candidate Containment Alloys
Nominal Compositions (weight percent)

Alloy	C	Mn	Cr	Ni	Co	Mo	W	Fe	Other
310S S.S.	.08	2.0	25	20				49.3	2 Mn, 1.5 Si, .045 P, .03 S
304 S.S.	.08	2.0	19	10				67.8	2 Mn, 1 Si, .045 P, .03 S
316 S.S.	.08		17	12		2		65.5	2 Mn, 1 Si, .045 P, .03 S
347 S.S.	.08		18	11				68.2	.8 Ta, .8 Nb, .03 S, .045 P, 1 Si.
Inconel 617	.07		22	54	12.5	9			1.0 Al
Rene 41	.09		19	55.3	11	10			1.5 Al, .01 B, 3.1 Ti
Hastelloy N	.06	0.8	7	69.5		16.5		5	1.1
Hastelloy X	.10	1.0	21.8	47	1.5	9	.6	18.5	1.5
Hastelloy C	.08	1.0	15.5	54	2.5	16	4	5.5	3
Haynes 25	.10		20	10	48.9		15	3	3
Haynes 188	.10		22	22	37.4		14	3	1.5
Refractaloy 26	.03	0.8	18	37	20	3		16.2	2.8 Ti, 1.0 Si, 0.2 Al

by uniform attack, pitting and intergranular attack. The dissolution of the container is sometimes referred to as leaching. Weight losses through impingement attack, corrosion-erosion and cavitation-erosion (pitting due to formation and collapse of vapor bubbles at a dynamic metal-liquid interface) are probably not of concern in heat pipes because of the low liquid flow velocities. Intergranular corrosion occurs when the grain boundary (anode) reacts with a large adjacent grain (cathode) with a resulting material removal from the boundary producing with a loss of strength and ductility. The result can be a catastrophic failure. Cracking can occur from repeated tensile stresses in the corrosive environment or by a constant tensile stress (stress corrosion cracking). The stress may arise from cold working or heat treatment as well as from externally applied loads.

The composition and variations in composition of the containment metal can be important in determining the corrosion tendency of a metal. Composition differences which might occur between adjacent grains as well as general inhomogenities can set up pitting due to galvanic action. Dissimilar metals in contact can have the same result. Weld areas, where compositional changes can occur, should be heat treated to insure homogeneity of the material.

The Na purity will be of prime importance in determining the corrosion rates of containment metals. Oxygen content is very important as well as the flow velocity of the liquid metal. Impurities in either the container or liquid could be undesirable. In the heat pipe, impurities

Table 4

Containment Alloy Properties at 1088°K/1500°F

Alloy	Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation %	Rupture in. 1000 hr.	Creep 14, 1000 hr. 1000 psi	Thermal Conductivity Btu/ft ² /hr/°F/in	Electrical Resistance μohm-in.	Melt. T °K/°F
304 S.S.	30 (2)	20 (2)	40 (2)	3 (2)	1.2 (2)	9.4* (2)		1658/2500 (9)
316 S.S.	30 (2)	20 (2)	40 (2)	8 (2)	2.8 (2)	9.0* (2)	74* (2)	1663/2560 (9)
347 S.S.	30 (2)	20 (2)	50 (2)	4.5 (2)	2 (2)	9.3* (2)	73* (2)	1685/2600 (9)
Inconel 617	50 (3)	25 (3)	95 (3)	16 (3)	5 (2)	179/94* (3)	72.7/48* (3)	1591/2430 (3)
Inconel 718	70 (8)	70 (8)	50 (8)	58 ⁺ (8)		167/77* (8)	52/49.4* (8)	1533/2300 (8)
Hastelloy N	56 (2)	29 (2)	24 (2)					1603/2430 (2)
Hastelloy X	50 (2)	30 (2)	33 (2)	9.7 (2)	7.4 (2)	174/76* (5)	46.6* (5)	1533/2330 (2)
Hastelloy C	60 (2)	35 (2)	55 (2)	15 (2)		67* (5)	51* (5)	1578/2308 (2)
Haynes 25	60 (4)	35 (4)	25 (4)	17 (4)	9 (2)	172/74* (5)	34.9* (5)	1602/2425 (2)
Haynes 188	83 (6)	41 (6)	60 (6)	16 (6)	10 (6)	174/84* (5)	36.3* (5)	1575/2375 (2)
Rene' 41	130 (2)	112 (2)	5 (2)	28 (7)		168/87* (5)	50.4* (5)	1583/2430 (2)
Refractalloy 26	80 (2)	80 (2)	10 (2)	18 (2)				

() Reference
 * Room Temperature
 + 1300°F

are swept with the liquid to the evaporator. The concentration of impurities can thus be very high as compared with that found in an arbitrary sample of the Na. The system temperature and temperature differentials can also be important factors influencing corrosion.

In the case of a directly heated clad (pass D.C. through the container walls for heating) the current may increase a number of the electrochemical oriented corrosion phenomenon.

Static corrosion of stainless steel, nickel and nickel based superalloys in sodium near 1300°K for a few hundred hours is very limited. Extensive pumped loop Na testing has been done on stainless steels including 18-8-2, 304, 316, 347 and others. Data available in the literature usually include the parameters, maximum temperature, temperature gradients, sodium flow velocity, impurity levels of oxygen and carbon and operating time. The resulting corrosion often varies considerably by changing one of the parameters. A summary for 316 stainless steel and for 304 stainless steel from the literature is that they can be used up to 850°K in sodium flow provided that the oxygen and carbon impurities level in the sodium are kept low (< 10 ppm). Transfer of interstitial elements to and from sodium exposed austenitic surfaces is possible in systems being considered here. When austenitic and ferritic steels are commonly exposed to the sodium environment, migration of carbon can occur resulting in a decrease in strength of the carbon depleted material while embrittling the carbon-rich system. In a pure 304 stainless steel, sodium flow system, acceptable performance appears to be obtainable as long as the oxygen level in the sodium is maintained at a few parts per million.

316 stainless steel has characteristics similar to 304 stainless steel.

Very little work has been done on the sodium corrosion of superalloys. Some data is available for Na flow systems appropriate for LMFB applications, but not for the low flow rates experienced in heat pipes.

In private communications (Ref. 9) the general trends of Na corrosion of alloying elements commonly found in superalloys and stainless steels indicate that the solubility of Ni in Na is higher than that of Fe. The solubility of Co is probably intermediate between Ni and Fe. In general, fluoride salts tend to leach Cr from the containment material. Hastelloy N was developed specifically for thermal energy storage applications such as this. Although the Hastelloy N compatibility with the salt is very good, at the temperature required here the material has a relatively low strength and is probably not an acceptable candidate. In order to obtain optimum conditions for a system such as this it might be desirable to have a duplex tube with an Fe-based alloy on the Na side and a Ni-based alloy, such as Hastelloy N, on the fluoride side. Also in private communications (Ref. 10) it has again been indicated that corrosion tests generally indicate that Ni and Cr are less corrosion resistant than Fe for sodium applications. It was again indicated that Hastelloy N with a Cr content of 7% as opposed to 22% for Inconel 617 or 23% for Inconel 601 would be better with the salt since the Cr can be leached by the salt at the hot end and deposited at the cold end, changing the composition along the length of the heat pipe and changing its physical characteristics. The Hastelloy N because of its low Cr content does not have the oxidation resistance of other superalloys

and it has low, high temperature strength in comparison with the other candidates listed.

Further personal communications (Ref. 11) again indicate from general test results that Co-based alloys are very resistant to Na corrosion, better than Ni, and that Fe is also better than a Ni-based alloy. It appears generally that the results of corrosion studies including Na on superalloys is very inconclusive. Most of the high temperature physical properties have not been obtained in the Na environment where the results could be completely different. The corrosion studies that have been obtained have been accomplished under varying conditions, many of which cannot be compared on a direct one-to-one basis. The results are often different and it is difficult to determine or to predict how a material is going to behave under any given set of conditions.

Table 5 is a summary based upon the literature survey of corrosion studies and a qualitative prediction of behavior with temperature, flow rate, and oxygen impurities as parameters.

Table 6 summarizes some sodium heat pipe results from the literature. The oxygen contents of the sodium and flow rates were again not available. The reports indicate that in most cases the heat pipes did not fail. The studies in general do not report post test analyses to provide data on corrosion that has taken place. Thus it is impossible in most cases to make any predictions for long term behavior. Since heat pipes are important candidates for many thermal applications, it will be necessary to obtain more reliable corrosion data in order to design practical systems for long term use.

Table 5
Sodium Heat Pipe Performance
From Literature

Manufacturer	Containment Material	Operating Temperature	Operating Time (hrs.)	Failure Mechanism	Reference
Dynatherm	304 S.S.	923°K (1200°F)	16,500	None	12
RCA	304 S.S.	1073°K (1112°F)	12,760	Terminated	13
Xerox/EOS	321 S.S.	1000°K (1500-1600°F)	9,000	Terminated	14
LERC	304 S.S.	1000°K (1341°F)	--	Continuing	15
RCA	316 S.S.	1044°K (1420°F)	11,860	Failed, evaporator pinhole	13
RCA	(A) Nickel	1073°K (1112°F)	20,000	Terminated	16
RCA	Hastelloy X	988°K (1319°F)	33,100	Terminated	13
Dynatherm	Haynes 25	1005°K (1350°F)	12,000	Terminated	17
Brown-Boveri	Nb - 1% Zr	1000°K (1341°F)	28,000	Two leaks (fixed)	18
LERC	Nb - 1% Zr	1000°K (1341°F)	3,000	Continuing	15
Euratom	Nb - 1% Zr	1123°K (1562°F)	16,000	Continuing	19
Xerox/EOS	Inconel 600	1600°F @ 150 w/in ²	-10,000	Continuing	20

Table 6
Relative Corrosion of Austenitic Steels and Superalloys

Alloy	T °F	Velocity	Life	(Impurities) Oxygen	General Attack	Strength
304, 316, 347	1000	High	Unlimited	Limited to few ppm	Minimum	Good
304, 316, 347	1000 to 1200	High	Dependent	Limited to few ppm	Moderate	Moderate
304, 316, 347	1500	Low	Limited	Limited	High	Poor
Superalloys (Ni based)	< 1300	Low	Good	Low	Low	Good
Superalloys (Ni based)	> 1300	Medium	Limited	Low	Several times greater than for stainless Ni leaching	Reduced
Superalloys	1300 to 1500	Low	Limited	< 20 ppm	Decarburiz- ation	Reduced creep strength
Superalloys	1300 to 1500	Low	Long	Few ppm	Low attack as long as Oxygen content is low	Good

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The evaporation of high vapor pressure alloying elements usually involved in stainless steels and superalloys have been identified. At the operational temperature of the thermal energy storage system of 1400°F it has been shown by mass spectrometer evaluation that some elements such as Mn may be depleted into space from some alloys. The very high vaporization rates have been demonstrated for at least one superalloy, Incoloy 800. As more superalloy vaporization tendencies are determined, the vaporization trends of the various elements can be evaluated. From these studies it might be possible to choose or design superalloys of particular compositions which would be best suited for the high temperature application for the thermal energy storage system. The possible life inhibiting characteristics of elemental loss from an alloy must be determined in order to evaluate the usefulness of a given alloy for this application.

High temperature physical properties including tensile strength, stress to rupture and creep strength have been obtained from the literature for a number of candidate superalloys. The high temperature corrosion behavior of some of these alloys and also of a couple of stainless steels have been obtained from the literature. A good deal of information exists in the literature with regard to compatibility of various stainless steels with sodium. Most of the experimental work that is in the literature was produced for the liquid metal fast breeder reactor program. The same corrosion considerations would be necessary in utilizing sodium in a thermal energy storage system as would be required for the LMFBR programs.

Little information exists in the literature in regard to the alkali metal compatibility with superalloys. The LMFBFR programs and the reported thermal energy storage program are now beginning to examine alkali metal-superalloy compatibilities because the strength of the candidate stainless steels are not sufficient for some projected applications. At the present, the most important corrosion parameters appear to be the oxygen content of the sodium and the flow rate. Since heat pipes are low flow systems, the alkali metal corrosion severity is much less in the heat pipe environment than it is for the LMFBFR applications. The literature indicates that heat pipes have lasted for tens of thousands of hours with sodium even though the LMFBFR programs have shown that under similar conditions, except for a high flow rate, the material would be rendered useless by way of corrosion. Unfortunately the heat pipe literature often does not contain post mortum tests of heat pipes to determine the extent of corrosion. Although a heat pipe might not fail, that does not mean that it has not corroded significantly. Quantitative analyses of alkali metal compatibilities with heat pipe structures are lacking. Mechanical properties of superalloys must also be evaluated in the sodium atmosphere. The high temperature mechanical properties listed were produced either in vacuum or in air. Stress corrosion and other characteristics can be entirely different in a sodium atmosphere. At the present time little information is available with regard to the behavior of superalloys with alkali metals in general.

The literature on Na heat pipes indicates that little information

is available regarding the wicking parameters of Na with composite wicks. Appropriate wicking parameters must be measured in order that heat pipe performance with composite wicks can be estimated. The design of pipes with simple regular wick geometry is straightforward, whereas additional experimental parameters are necessary for wicks such as the ones required for this application. Determination of the wicking parameters of Na is difficult since it must be performed in an evacuated system at elevated temperature.

In order to insure compatibility and long life for the sodium heat pipe/thermal energy storage system a test program should be followed which will provide direct design information. A program to provide guidelines for the present Na heat pipe systems should include at least the following efforts.

1. Life tests of sodium heat pipes should be performed with a variety of superalloy containers in a vacuum environment. Vacuum life test stands need to be established. Numerous materials can be tested with small samples in the Na environment. A few of the most promising candidates should be fabricated into heat pipes with a full heat transfer rate equivalent to the ultimate system so that all possible corrosion mechanisms can occur. Post test corrosion evaluation should follow the life tests with a number of identical pipes being evaluated at prescribed intervals.
2. The performance of candidate wick structures with Na must be measured in order to supply data for the accurate design

of Na heat pipes. The tests must be performed in a vacuum at elevated temperature. Wicking height is a prime parameter.

3. Corrosion tests should include appropriate methods of container (cross sectioned) evaluation (mass spectrometer, microprobe, x-ray diffraction, metallographic, etc.) both on the Na side and the vacuum side.
4. Procedures for Na handling and heat pipe filling should be established, including cleaning procedures for all Na contact surfaces, and for disposal of Na wastes.
5. The Na should be "clean" (less than 10 ppm O_2) prior to testing, and should be assayed after the test.
6. Any critical mechanical properties such as creep should be considered for further testing if the capsules demonstrate any appreciable compositional changes during the life tests.

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